

THE NEUTRAL INTERPLANETARY MEDIUM

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Abstract

Most of the hydrogen (H) and helium (He) gas in the interplanetary medium originates in the nearby interstellar medium. Detection of the solar Lyman- α (1216A) and solar 584A lines by measurement of the backscattering has led to the concept of the "interstellar wind." The recent OGO-5 Lyman- α maps are all consistent with this concept. Models for the nearby interstellar gas properties give $n(\text{H}) = 0.05 - 0.2 \text{ cm}^{-3}$, $n(\text{He}) = 0.003 - 0.04 \text{ cm}^{-3}$, $T(1000 - 10,000^\circ\text{K})$, and $v_0 = 3 - 20 \text{ km sec}^{-1}$, where n is the number density, T is the gas temperature and v_0 is the relative velocity of gas and solar system. Recent Lyman- α measurements from OGO-5, Mariner 9, and Apollo 17 indicate a less intense Lyman- α minimum (~ 100 Rayleighs) than previously reported, in agreement with earlier results from the VELA satellites. Lyman- α airglow results indicate a more intense solar Lyman- α line than previously accepted, implying a net repulsion of hydrogen atoms from the solar system due to radiation pressure. Under these circumstances, a density build-up is expected in a "hydrogen sheath" region, which is paraboloidal in shape with an axis of symmetry along the wind-sun vector.

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I. Introduction

All of our present knowledge of the neutral interplanetary medium comes from measurements of the Lyman alpha hydrogen (H) 1216A and helium (He) 584A resonance lines. Because the Lyman alpha (Ly- α) emission is weak compared to scattering from H in the earth's geocorona, the extraterrestrial Ly- α line must be measured at great distances from the earth. The extraterrestrial 584A line can be measured at night at low altitudes where no appreciable 584A airglow is present. Only recently have these two emissions been observed in a systematic way. Consequently the study of neutral interplanetary gas is a comparatively new area, and is now in a state of rapid advancement, as new observations become available.

In this paper I will pay particular attention to the newest observations, many of which are not yet published. I will describe how these results fit into the currently accepted picture, and how future measurements can help to answer some of the unsolved problems. What follows will consist more of a status report, rather than an in-depth review. For more details on the basic theory and equations see Axford¹ and Fahr².

II. Measurements of the 1216A Lyman Alpha Sky Background

Up until 1969, only a few isolated scans of the sky had been made at this wavelength from planetary fly-by spacecraft and high apogee satellites (see Thomas and Krassa³ for a comparison of these measurements). It was unclear at that time whether the observed emission (of the order of a few hundred Rayleighs) is correlated with galactic sources⁴ or has its origin in the nearby interplanetary medium⁵.

To answer the above questions, the OGO-5 spacecraft, carrying two Ly- α photometers, was placed into a special "spin-up" mode. The body-fixed photometers were made to scan the sky in a systematic fashion at altitudes near 130,000 km, above most of the scattering from terrestrial hydrogen. All-sky maps for the first three spin-up operations have been reported in 1971^{3,6}. The following properties were revealed: (1) the glow is a smoothly-varying function of direction with no galactic symmetry and no correlation with astronomical sources; (2) the only distinctive features are a broad maximum and minimum, separated by about 180° and both situated in the ecliptic plane. An ecliptic symmetry was evident in the isophotes; (3) the maximum feature showed a seasonal shift of



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about 40° , an indication of an interplanetary source, i.e., scattering by nearby hydrogen of the solar Ly- α line.

These properties could be explained by the model of Blum and Fahr⁷ who predicted the distribution of interstellar gas in the vicinity of the solar system. They showed that, due to the relative motion of the sun and the nearby gas, interstellar neutral gas could penetrate the inner solar system. However since the maximum brightness should coincide with the upwind direction, it was surprising that the observed maximum is not located at the classical apex of motion in the constellation Hercules, but 60° away in the Sagittarius-Scorpius region. This discrepancy could be accounted for if the nearby gas had its own peculiar motion, separate from the mean motion of nearby stars⁸. The coincidence of this motion with the ecliptic plane is curious⁶ but there appears to be no other reason for the observed symmetry.

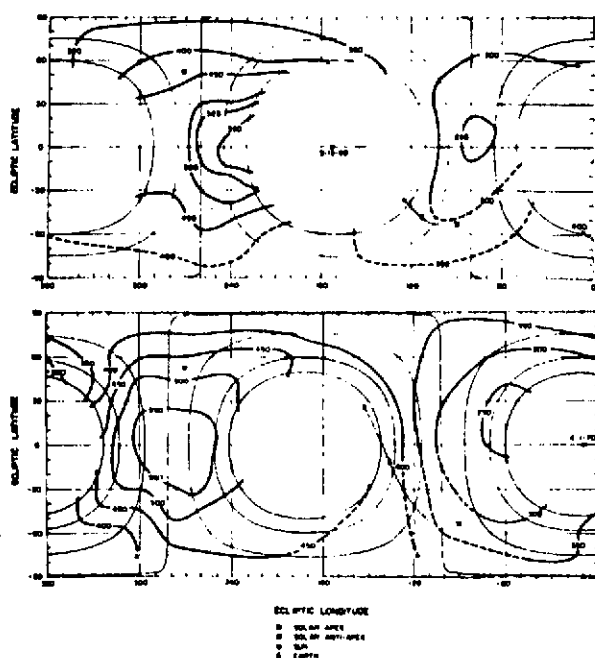


Fig. 1 Ly- α isophotal maps for the solar maximum periods September 13, 1969 (SU-1) and April 1, 1970 (SU-3)³. Solid lines are isophotal contours in Rayleighs. Dashed contours indicate interpolations beneath geocoronal scattering.

The maps for the first and third spin-ups (SU-1 and SU-3) are shown in Fig. 1. The displacement of the maximum over a six-month period is obvious. The motion of the minimum (if present) is not apparent. The results from the fourth spin-up (SU-4) are shown in Fig. 2, and confirm the parallax argument. Two additional spin-ups followed in March 1971 (SU-5) and May 1971 (SU-6). Failure of the spacecraft's attitude-control system occurred in July 1971 before additional spin-ups could be performed.

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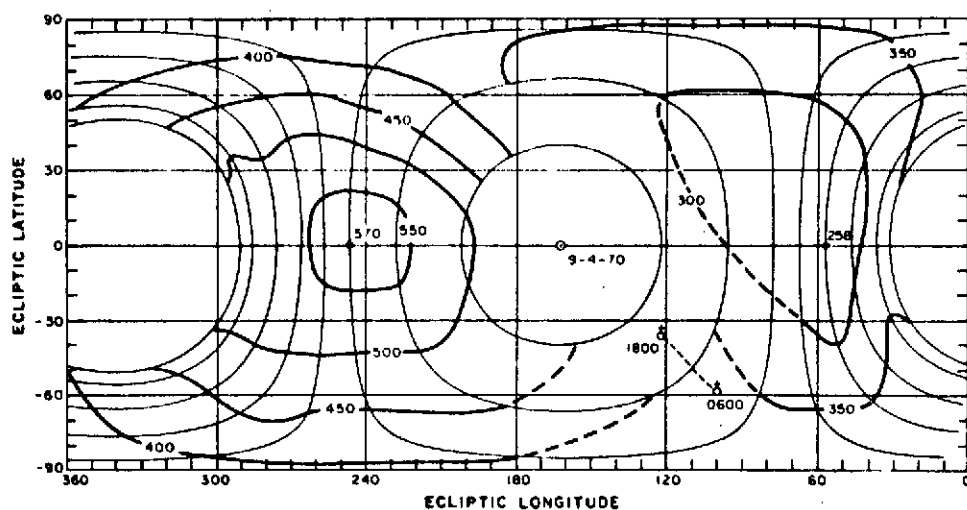


Fig. 2 Ly- α isophotal map for September 4, 1970 (SU-4), same format as Fig. 1⁹. The numbers next to the earth symbols indicate the universal times of the beginning and end of the spin-up period. The earth moved over the indicated path during this period.

The results for SU-5 in the vicinity of the maximum are given in Fig. 3, along with the earlier results. Thomas and Krassa⁹ have shown that the apparent discrepancy of the SU-5 maximum position is almost certainly due to the increased geocoronal contamination. This happened as a result of a contracting orbit, so that most of the measurements were being made below 110,000 km. At this distance (17 earth radii), scattering from terrestrial hydrogen above the spacecraft causes an appreciable distortion of the isophotes. There is also some evidence of the 'geotail'¹⁰ in several of the maps constructed from data taken during this period. An attempt was made to correct for geocoronal effects, and the results, although not entirely satisfactory, show that the position of the maximum was shifted to $RA = 273^\circ \pm 13^\circ$, which is not inconsistent with the position of SU-3, $RA = 283^\circ$.

There remains the possibility that the wind direction itself shifted, or that an appreciable change in the interplanetary distribution occurred. The latter could result from an appreciable change of the ionizing solar wind flux in 1971, as suggested by Biermann¹¹. However as discussed by Blum and Fahr¹², the ionization rates must be averaged over many solar rotations. Shown in Fig. 4 are the effective ionization rates of neutral hydrogen from charge exchange. These remained fixed during the entire OGO-5 lifetime so that



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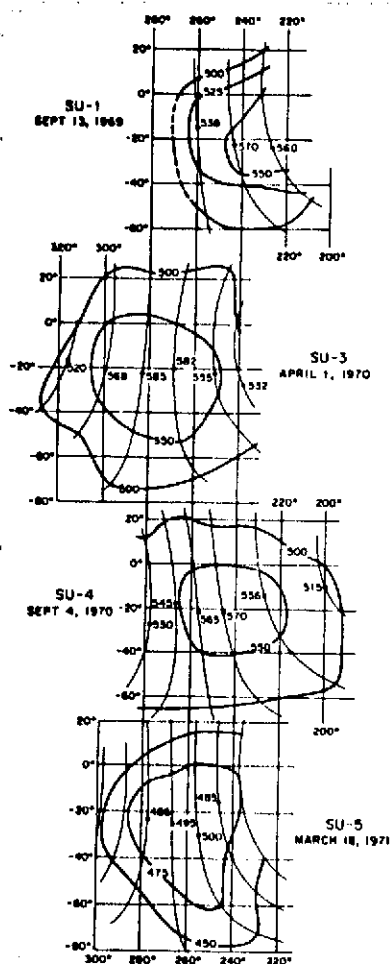


Fig. 3 Comparison of the Ly- α isophotes in the vicinity of the Ly- α maximum for four different periods, each separated by about six months⁹.

sun's ultraviolet radiation ionizes the gas at some characteristic penetration depth, depending upon the species. For hydrogen, the expanding solar wind provides the main ionizing mechanism through charge exchange of protons with the incoming hydrogen atoms. Electron ionization provides an additional 5% contribution¹⁴. I will confine the discussion to hydrogen and helium, the only interplanetary species for which we have direct evidence so far.

the interplanetary distribution should have been stable throughout this entire period⁹. An apparent migration of the Ly- α maximum could occur as a result of anisotropy in the solar Ly- α emission^{13,2}. Thomas and Krassa⁹ argued that these effects, at least for the spin-up periods, are also negligible. Finally, a changing radiation pressure force due to variable solar Lyman alpha emission ought to be less important than variable ionization rates, since ionization is more important in changing the hydrogen distribution than radiation pressure (see Section VII).

Summarizing the OGO-5 data, all maps confirm the general model of the 'interstellar wind.' I will now describe in more detail our present concept of the interplanetary gas distribution.

III. The Interstellar Wind

The motion of the nearby interstellar gas causes a "wind" to blow past the sun. In analogy to a desert thunder storm where the raindrops may evaporate before striking the ground⁵, the

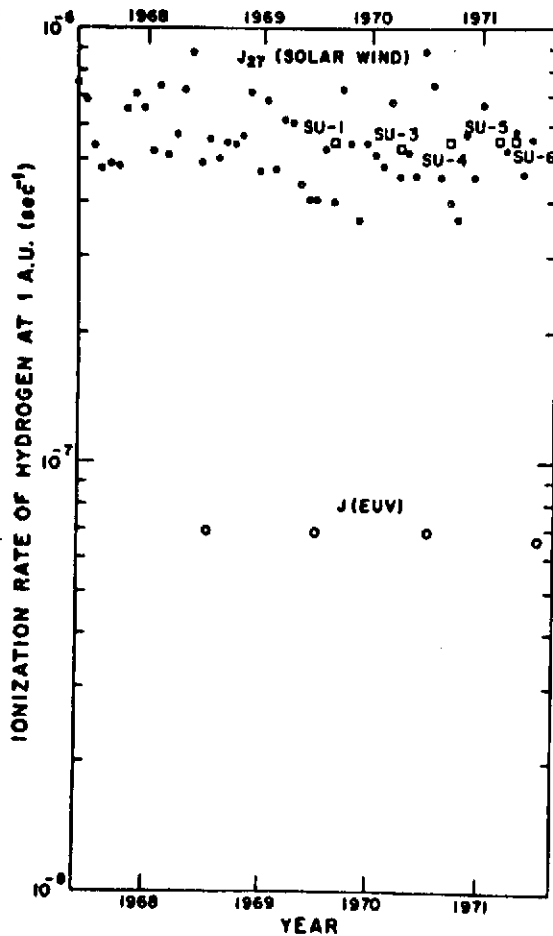


Fig. 4 Ionization rates for hydrogen from solar wind charge exchange (J_{27}) averaged over a 27-day period. Also yearly averages of the EUV ionization rates, $J(\text{EUV})$. The squares are long-term averages for the six spin-up periods (SU-1 through SU-6).

The nearly spherically-symmetric ionization acting on the incoming flow produces an elongated cavity, symmetric about the flow axis, with its near point in the upwind direction (Fig. 5). To determine the density distribution, the forces acting on the atoms must be specified. For He, only solar gravitation is important. For H, the solar Ly- α line is sufficiently intense that an appreciable radiation pressure force acts on the H-atoms. As discussed later, the net effect is to "blow" the atoms away from the sun. Typical trajectories are shown in Fig. 6 for He and H. The ratio of radiation pressure to gravitational force is denoted by μ .

For He, the downwind direction is populated by atoms whose Keplerian trajectories curve around the sun. In addition, a random distribution of velocity components (an interstellar gas temperature) will produce some high-velocity atoms which penetrate the downwind region from the side and even from the "wake" direction. For H, only

the latter mechanism is operative. The effects of the gas temperature are most noticeable for He in the downwind direction, where they tend to smear out a density enhancement along the axis (for 0°K , there is a density singularity). The

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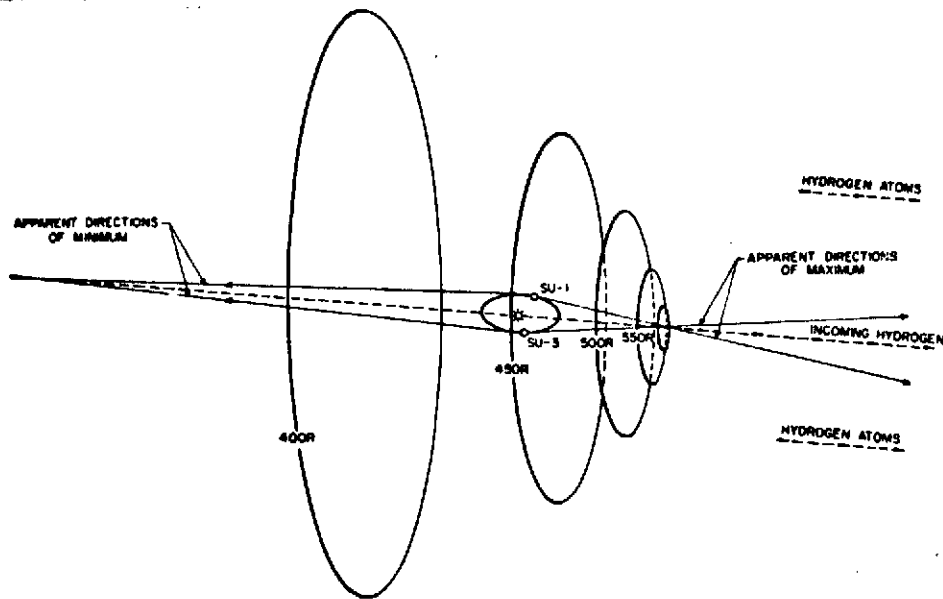


Fig. 5 Schematic diagram of the geometry of the interstellar wind. Each circle, centered on the sun-interstellar wind axis, is the locus of equal volume emission rate of Ly- α scattered by interplanetary hydrogen atoms.

influences of temperature are important for H in both hemispheres, providing the sole reason for a finite column density in the wake. In the absence of a galactic contribution and multiple scattering of Ly- α photons, all of the Ly- α intensity in the minimum region is accounted for by temperature effects. A velocity distribution also smears out the density enhancement in the "hydrogen sheath" region (see Figs. 9 and 16), to be discussed later.

To estimate the dimensions of the hydrogen and helium cavities, it is necessary to consider the combined effects of ionization, gravity, and radiation pressure. The simplest case is the upwind direction, where the atoms approach on straight lines ($\mu = 1$). The upstream distance $r_i(0)$ where the atoms have a probability of $1/e$ of being ionized is

$$r_i(0) = J_e r_e^2 / v_0 \quad (1)$$

where J_e is the total ionization rate at the solar distance r_e , and v_0 is the initial wind velocity (in this case the velocity is constant throughout the medium). For the more general case ($\mu \neq 1$) some typical trajectories are shown in

Fig. 6. It can be easily shown that the upstream penetration distance for a single atom approaching from the upwind direction, $r_{pe}(0)$, is given by

$$r_{pe}(0) = r_i(0) \left(1 - r_p(0)/4r_i(0)\right)^{-1} \equiv r_i(0)f \quad (2)$$

where $r_p(0) = \frac{2GM(\mu-1)}{v_0^2}$. G is the gravitational constant and

M is the solar mass. The quantity $r_p(0)$ has no physical significance when $\mu-1 < 0$. However when $\mu-1 > 0$, it represents the upstream distance of closest approach, i.e., where an atom approaching the sun radially is brought to rest before being

'blown away'.

The quantity f is the correction for a finite repulsive or attractive force.

For H, $J_e = 6.15 \times 10^{-7} \text{ sec}^{-1}$ at one astronomical unit (1 A.U.)⁹ and for He, $J_e = 0.65 \times 10^{-7} \text{ sec}^{-1}$ at 1 A.U.¹. Assuming an initial velocity v_0 of 20 km sec^{-1} , $r_p(0) = 1.9 \text{ A.U.}$ (H) and $r_p(0) = -4.43 \text{ A.U.}$ (He) where $\mu-1$ for H was taken to be 0.43 (see Section VI). Finally, the correction factors f and penetration depths are: $f(\text{H}) = 1.12$, $f(\text{He}) = 0.307$, $r_{pe}(0) = 5.01 \text{ A.U.}$ (H) and $r_{pe}(0) = 0.15 \text{ A.U.}$ (He).

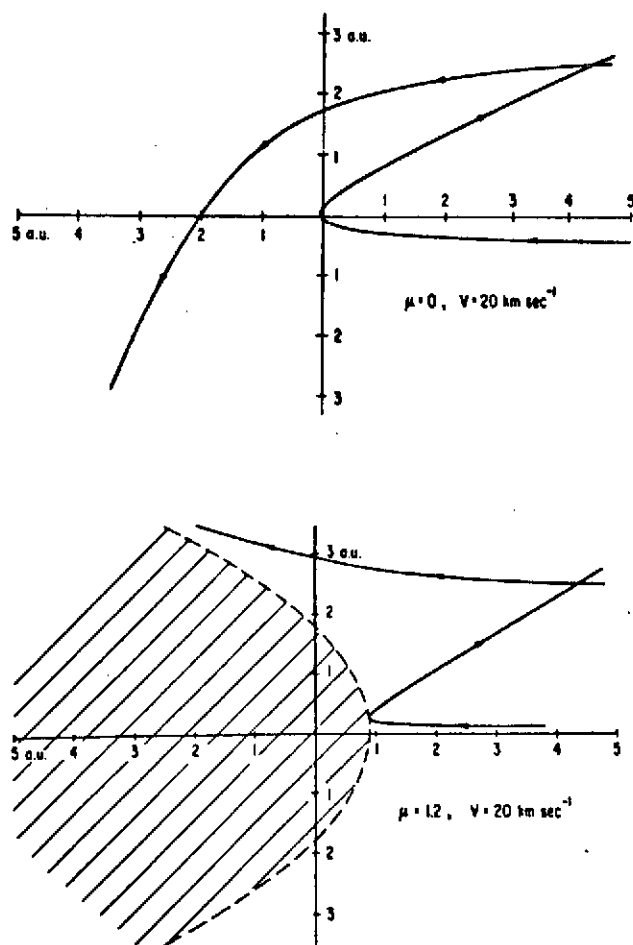


Fig. 6 Typical trajectories for helium atoms ($\mu = 0$) and hydrogen atoms ($\mu = 1.2$). μ is the ratio of the radiation pressure force to the solar gravitational force¹.

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These values show that a typical hydrogen atom approaches the sun within about 5 A.U. (about the distance of Jupiter). In contrast, helium penetrates to well within the orbit of Mercury. Unfortunately these figures should be regarded as uncertain to within a factor of 2 to 3 mainly due to the uncertainty in the value of v_0 . A more accurate value for hydrogen is determined from the observed parallactic displacement of the maximum. On this basis the penetration depth lies between 4 A.U.⁶ and 5 to 10.9 A.U. depending upon the temperature of the model⁸.

The theory for the density distribution uses the basic equations of motion and continuity. For the cold model, these equations can be integrated analytically^{7,15}. Axford¹ presented detailed contours of equal density for He and H. A few of these are shown in Figs. 7 and 8. Note the effect of the density singularity on the helium contours, and the presence of a hydrogen void in the "forbidden" region near the sun for $\mu > 1$.

The various published models fitted to the OGO-5 spin-up data are summarized in Table 1.

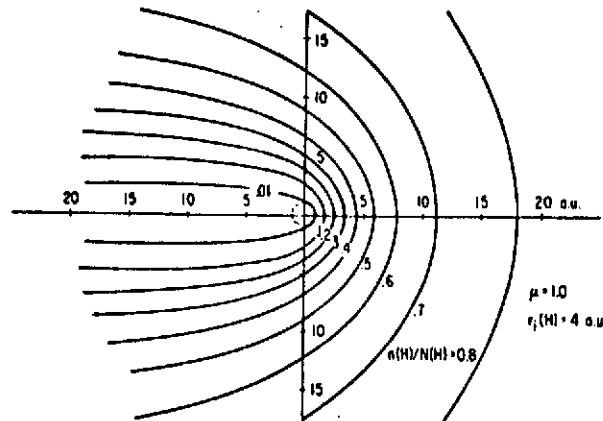


Fig. 7a Density contours for cold hydrogen ($\mu = 1$). $n_{\infty} = 1 \text{ cm}^{-3}$, $v_0 = 20 \text{ km sec}^{-1}$, r_{pl} (denoted by r_i in the figure) is 4 A.U.

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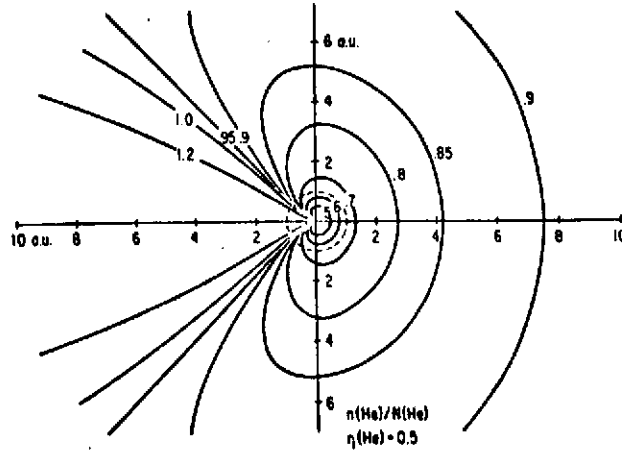


Fig. 7b Density contours for cold helium ($\mu = 0$). $n_{\infty} = 1 \text{ cm}^{-3}$, $v_0 = 20 \text{ km sec}^{-1}$, r_{pl} (disregard the $r_i = 0.5$ in the figure) is taken to be unity.

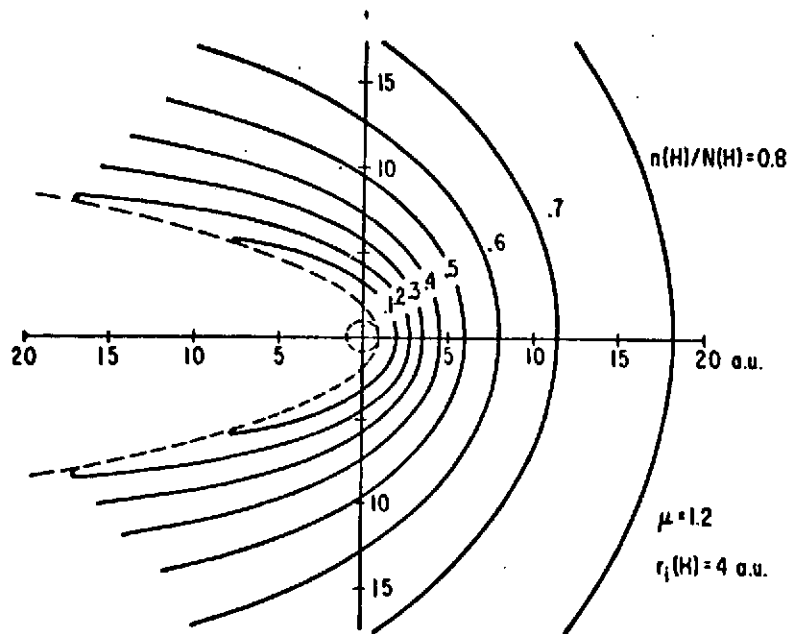


Fig. 8 Density contours for cold hydrogen for 20% overbalancing of radiation pressure¹.

	Thomas ⁸⁺		Bertaux ^{16*}		Fahr and Lay ¹⁷
	hot model	cold model	hot model	cold model	
Density n_{∞} (cm ⁻³)	0.12	0.06	0.12	0.08	0.1
Initial velocity v_0 (km/sec)	5	9	2-5 13-14**	5-9	20
Temperature T (°K)	3,600	0	9000-15,000 200-1100**	4000-10,000	4000-6000
Ionization rate (sec ⁻¹)	3.9×10^{-7}		4.63×10^{-7}		5.6×10^{-7}

⁺ Complete balance, $I_{\max}/I_{\min} = 2.38$, $J = 3.9 \times 10^{-7} \text{ sec}^{-1}$

*20% overbalance, $I_{\max}/I_{\min} = 2.46$, $J = 4.63 \times 10^{-7} \text{ sec}^{-1}$

**Same as *, but with $I_{\max}/I_{\min} = 4$

Table 1

SUMMARY OF INTERPLANETARY HYDROGEN MODELS

IV. Additional Sources of Interplanetary Gas

In addition to the interstellar contribution, three other sources of gas may be important:

"Hot" H-atoms From the Shock Region

These are produced by solar wind protons whose velocities have been randomized in the turbulent region downstream from the solar wind shock transition^{18,19,20}. These protons with velocities of several hundred kilometers per second will charge exchange with interstellar hydrogen atoms. A certain fraction of hot neutrals will be "sprayed" into the inner solar system. The relative importance of this component depends upon the number of cold atoms that successfully enter the heliosphere without charge exchange. Fahr² has shown that if $v_0 = 20 \text{ km sec}^{-1}$, this fraction is negligible. If $v_0 = 5 \text{ km sec}^{-1}$, they could be as abundant as the cold atoms. However their contribution is probably negligible as most of them would be unobservable in Ly- α , since their Doppler shifts would be of the order of 1.5A, well out of the solar line width.

Dust-Associated Gas

Neutralization of solar wind ions can occur at the surfaces of interplanetary dust grains, leading to production of neutrals which are propelled outward by solar radiation pressure. Steady-state densities for H and He have been shown by Banks²¹ to depend upon the parameter G, the "dust deionization factor" (which is uncertain within a very large range). The density of the i th constituent at the solar distance r is given by

$$n_i(r) \approx \frac{\Phi_e^i G r_e}{J_e r} \quad (3)$$

where Φ_e^i is the solar wind flux of the corresponding ion at the distance r_e . The intensity I_i at an angle θ from the anti-solar direction as seen from the distance r_e is

$$4\pi I_i = \frac{g_i \Phi_e^i G r_e}{J_e (1 + \cos \theta)} \quad (4)$$

where g_i is the resonance g-factor, or excitation efficiency (sec^{-1}) for the particular line at 1 A.U. From Fig. 1, the sky intensity at $\theta = 130^\circ$ is 250 Rayleighs on the ecliptic. This may be regarded as the upper limit for the dust-

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associated component. Inserting the following values into Eq. (4), $\Phi_e^{H^+} = 3 \times 10^8 \text{ cm}^{-2} \text{ sec}^{-1}$ and $g_H = 2.56 \times 10^{-3} \text{ sec}^{-1}$, yields $G < 4.8 \times 10^{-18} \text{ cm}^{-1}$. This value is an order of magnitude smaller than values deduced by Banks²¹ from observations of He^+ in the solar wind and from Balmer $H\beta$ emissions that presumably arise in the interplanetary medium²². However the former mechanism is no longer accepted as the source of He^+ in the solar wind²³. Furthermore the observed Balmer emissions are most likely geocoronal in origin²⁴. The remaining determinations of G from zodiacal light measurements and rocket and satellite measurements of interplanetary dust all give values of G less than $5 \times 10^{-18} \text{ cm}^{-1}$.

It now appears that solar wind protons will emerge from interplanetary dust grains as molecular hydrogen. In analogy to lunar soil, the recombination of H to H_2 on the surfaces of the lunar grains is more than 99% efficient^{25,26}.

Comets

Bertaux and Blamont²⁷ pointed out that comets evaporate a large quantity of atomic hydrogen into interplanetary space. Hydrogen is produced by photodissociation of H_2O , OH , and possibly other hydrogen-bearing molecules²⁸. The possibility that comets are important for the overall interplanetary density can probably be ruled out from OGO-5 observations of the sky background during the period for which Comet Bennett (1969 III) was at perihelion in March 1970. No observable perturbation of the sky background emission was evident, although the comet itself was very bright in $\text{Ly-}\alpha$ ²⁹. This does not exclude the possibility of a significant contribution from large numbers of small comets, which would go unobserved in the visible. However this source alone could not account for the observed $\text{Ly-}\alpha$ distribution, since the distribution of the orbits of new comets is known to be nearly isotropic.

V. Interplanetary Helium

From cosmic abundance considerations, He should be present in the interstellar medium at a density of $\sim 10\%$ of H (or about 0.01 cm^{-3}). However the "filtering" action of solar wind ionization on H will cause He to be the dominant neutral species in the inner solar system (inside 5 A.U.). One might expect that He would be easily observable through the backscattering of the solar $\text{He I } 584\text{\AA}$ line. However two factors contribute to making the 584A measurement difficult: (1) the resonance g -factor is only about 1% of that of $\text{Ly-}\alpha$, (2) 584A lies in the extreme ultraviolet region where detector

technology is less advanced. Partially offsetting these disadvantages is the fact that extraterrestrial 584A can be observed at night from a low-apogee orbit. Before discussing the available measurements, I will first consider the expected density distribution.

As discussed earlier, the interstellar wind theory predicts a pronounced "helium cone" on the downwind axis as a result of gravitational focussing. This is illustrated in Fig. 9. The influence of temperature in smearing out the density enhancement can be estimated by an approximate analytic formula due to Feldman *et al.*²³. The number density on the downwind axis is given by

$$n(r) = n_{\infty} (v_0/v_T) (\pi |r_p(0)|/r)^{1/2} \exp \left\{ -\pi (r(0)/r)^{1/2} \right\} \quad (5)$$

v_T is the interstellar thermal velocity. Provided $v_T \ll v_0$, Eq. (5) is valid for $\mu < 1$. According to Johnson³⁰ this formula applies only for values of r which do not greatly exceed the cavity size. However since this limitation is not involved in the derivation, this assumption is not necessary. It has the correct asymptotic limit at $r \rightarrow \infty$, i.e., $n_{\infty}(r \rightarrow \infty, \theta = 180^\circ) = 0$. It is obvious that the downstream number density can be much higher than in interstellar space. The restriction $v_T \ll v_0$ implies a temperature $\ll 100,000^\circ\text{K}$ for the nearby intercloud medium. This is reasonable on the basis of 21-cm evidence indicating the intercloud temperature lies between $1,000^\circ\text{K}$ and $5,000^\circ\text{K}$ ³¹. The radial dependence of the helium density for a model consistent with the "hot model" of Thomas⁸ is plotted in Fig. 9. For $n_{\infty}(\text{He}) = .01 \text{ cm}^{-3}$ and $T = 3500^\circ\text{K}$ the helium column density inside 1 A.U. is $1.3 \times 10^{12} \text{ cm}^{-2}$, corresponding to an optical depth of 0.1. It might be barely possible to observe the interplanetary attenuation of the solar He I 584A in a high-resolution experiment above the helium geocorona. The interplanetary helium atoms that reach the downstream axis may have a sufficiently high flow velocity so as to Doppler-shift the absorption outside the telluric absorption. However at a rocket altitude of 200 km, the helium geocorona has a vertical optical depth of ~ 30 , which could mask the interplanetary line. Such an experiment is planned by a group at the University of Colorado at the appropriate time of year (December 1974).

A theoretical calculation³ of the intensity enhancement in 584A is shown in Fig. 10. The appearance of the sky in 584A has also been predicted theoretically by Paresce and Bowyer³². In Fig. 11 are shown views on three different

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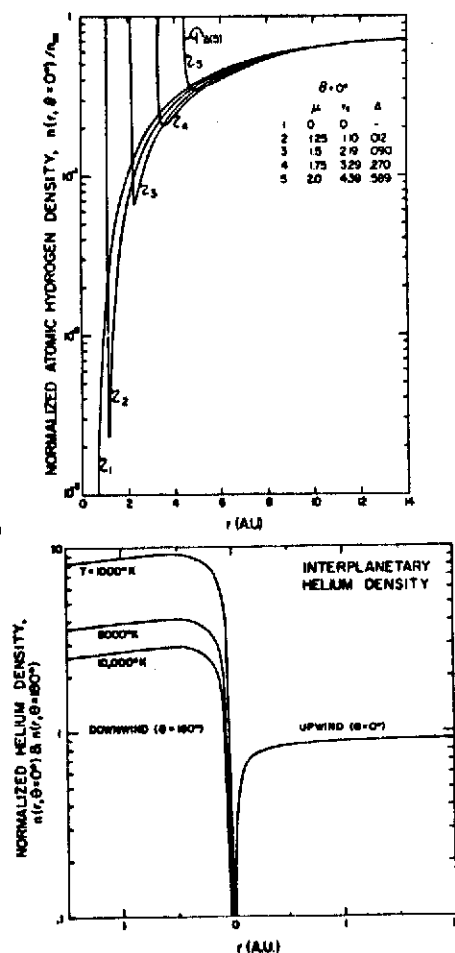


Fig. 9 Hydrogen and helium density profiles along the wind axis. Hydrogen densities for $T = 0^\circ K$ and $v_0 = 20 \text{ km sec}^{-1}$. Helium densities for $T = 0^\circ K$ are computed from Holzer¹⁵ for the upwind direction ($\theta = 0^\circ$). In the downwind direction, the densities are computed from Eq. 5.

dates. The top panel shows the expected sky distribution in June, when the earth is located on the upwind axis. The middle panel refers to the December period when the earth is located on the downwind axis. The bottom panel shows the expected contours for March (or September if the map is reflected about the sun). The assumptions were (1) that the solar 584A line width is $.015\text{\AA}$ ³³, (2) the wind speed v_0 is 10 km sec^{-1} , and (3) $T = 100^\circ K$. I will discuss each of these in turn: (1) the line width is an indirect determination from 584A airglow measurements, combined with a theory of multiple scattering in the helium geocorona. From the knowledge of the flux in the entire line of $1 \times 10^9 \text{ photons cm}^{-2} \text{ sec}^{-1}$ ³⁴, one can deduce the line width required to explain the airglow data of Donahue and Kumer³³. The result ($.015\text{\AA}$) is surprisingly low. It would also imply that for some viewing directions the Doppler effect in 584A is sufficiently large to shift the absorption frequency well outside the solar line. (For example for a line-of-sight velocity of 20 km sec^{-1} , $\Delta\lambda = .029\text{\AA}$.) Paresce and Bowyer³² calculated the 584A sky brightness for a range of parameters and found large variations in the expected intensity for certain viewing directions. (2) The wind speed is also a quantity which is not well known. In the model of Thomas⁸, v_0 varies between 5 and 10 km sec^{-1} . However Axford¹ and Fahr² assume $v_0 = 20 \text{ km sec}^{-1}$, and Bertaux et al.¹⁶ discuss an acceptable

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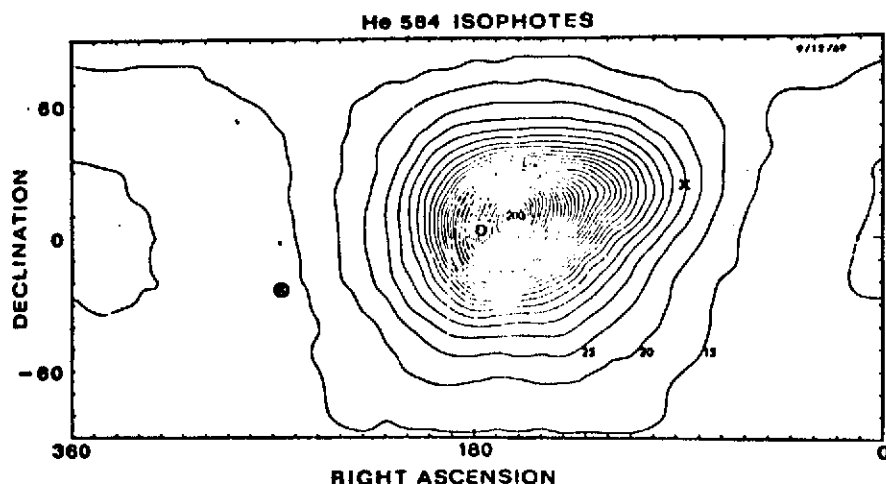


Fig. 10 Theoretical 584A sky map in celestial coordinates for September 12. Intensities are in Rayleighs and apply to $n_{\infty}(\text{He}) = 1 \text{ cm}^{-3}$. The circle indicates the position of the sun. An integration over a field of view was performed¹³.

model for which $v_0 = 3 \text{ km sec}^{-1}$. (3) A temperature of 100°K is probably too small. It depends upon whether one is willing to accept an isotropic Ly- α galactic background of a few hundred Rayleighs. If so (and theory has not yet ruled this out³⁵), very low temperatures are acceptable. However it is more likely that the solar system is immersed in the hot intercloud medium of the galaxy which occupies 90% of the total volume of the galaxy. As mentioned earlier, temperatures of several thousand degrees are therefore more appropriate. Finally, it is not yet clear that one can ignore multiple scattering of Ly- α photons in the more distant regions outside the cavity. Wallis³⁶ has suggested that a large (200 Rayleighs) isotropic background emission is produced from this source, whereas Fahr and Lay¹³ have claimed on empirical grounds that such an isotropic background is negligibly small. Holzer³⁷ has recently given persuasive reasons to believe that the Lyman alpha galactic background is very small. This question cannot really be settled until measurements of high spectral resolution become available.

I now turn to the available measurements of the sky background 584A line. In a review of rocket measurements through 1971, Meier and Weller³⁸ show that the daytime measurements are consistent with the concept of scattering in the helium geocorona, within rather wide error limits due mostly to calibration uncertainties. At night, a number of observations

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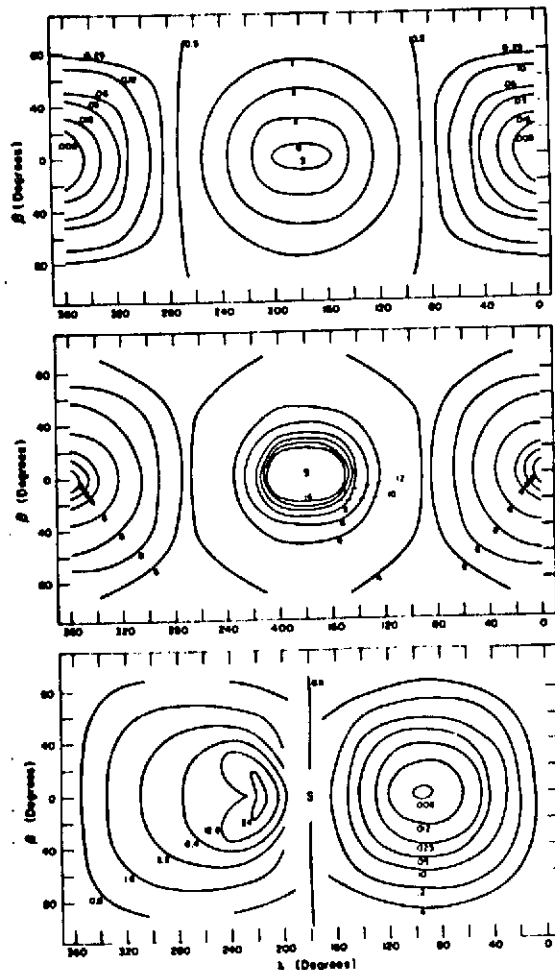


Fig. 11 Theoretical 584A sky map in ecliptic coordinates for three different positions in the earth's orbit. (a) June, (b) December, and (c) March. The contours are in Rayleighs, and are calculated for $n_{\infty} = .008 \text{ cm}^{-3}$, $T = 100^{\circ}\text{K}$, $v_0 = 10 \text{ km sec}^{-1}$, and a solar line width of $.015\text{\AA}$ ³².

interplanetary helium. The measured distribution over the sky bears some resemblance to the theoretical sky maps. The best fit to the data is obtained with $v_0 = 5 \text{ km sec}^{-1}$,

indicate more 584A emission than can be accounted for by multiple scattering around to the nightside. Ogawa and Tohmatsu³⁹ made nighttime rocket measurements up to 1600 km. However the presence of an appreciable geocoronal contribution could have masked up to 5 Rayleighs of extraterrestrial 584A emission. Young *et al.*⁴⁰ observed a count rate consistent with an emission rate of 1.4 Rayleighs for the anti-solar direction in October 1969. This is the intensity expected from a uniform density of $n_{\infty} = .003 \text{ cm}^{-3}$ of interplanetary helium, within a factor of 3 of the expected density. Paresce *et al.*⁴¹ have recently suggested that H Lyman- β measurements would not be subject to any outside contamination because it is absorbed in the interstellar medium. However, this approach may not be a practical one, as Skylab measurements by the NRL group show that solar Lyman- β emission is remarkably variable⁴². Paresce *et al.*⁴¹ have recently reported nighttime measurements of the 584A emission, which may be the first evidence for

$T = 10^4$ °K, and a 584A solar line width of 0.15Å. However the fit is far from satisfactory in certain portions of the map, and these values should be treated with caution.

More useful and extensive data can be obtained from earth-orbiting satellites or deep-space vehicles. In the former category is the NRL experiment on the Air Force Satellite STP-72-1, in orbit since October 1972 and still in operation. Preliminary results reported by Weller and Meier⁴³ indicate the presence at night of an extra-terrestrial component in the upward-looking photometer. The intensities are of the expected magnitude. An all-sky map is now in preparation. In the second category, the Pioneer 10 and 11 spacecraft each carry an extreme ultraviolet photometer experiment⁴⁴. Pioneer 10 has been en route to Jupiter since March 1972. Pioneer 11 was launched in April 1973. The trajectory of Pioneer 10 and the viewing directions of the photometer are shown in Fig. 16. The photometers have continuously recorded the 1216Å and 584Å sky background signals over a limited part of the sky. A preliminary analysis indicated that the Ly- α data are consistent with the OGO-5 maps⁴⁵. However the nominal position for the mean interstellar wind direction deduced from Pioneer 10 data was at an ecliptic longitude of $\sim 240^\circ$ ⁴⁶. This apparent discrepancy with the OGO-5 value of 263° could result from a combination of errors in both measurements (see postscript). The 584Å data also indicated an ecliptic symmetry for the helium isophotes. Future measurements of the helium and hydrogen lines are expected from an experiment on the Mariner Venus-Mercury fly-by, scheduled for launch in November 1973, and on the Mariner Jupiter-Saturn fly-by, scheduled for launch in the late 1970's.

VI. Recent Lyman Alpha Measurements and Their Implications

Bohlin⁴⁷ has recently reported deep-space Ly- α measurements from the Mariner 9 spacecraft at the positions shown in Fig. 12. The Mariner 9 spacecraft did not have the capability of controlled rolling maneuvers to obtain a continuous sky-mapping. However its scanning platform could be aimed at any selected point over a broad region of the sky. The measurements were made by a scanning ultraviolet spectrometer with 15Å spectral resolution and a field of view of 1.2° by 0.17° . Figure 13 shows a comparison of the results with the OGO-5 SU-1 map for which the geometry is most similar. The points near the maximum agree fairly well; however the Mariner 9 data near the Ly- α minimum are a factor of 2 below the OGO-5 values. It appears that this is a result of geocoronal contamination of the OGO-5 maps in this part of the sky. As discussed by

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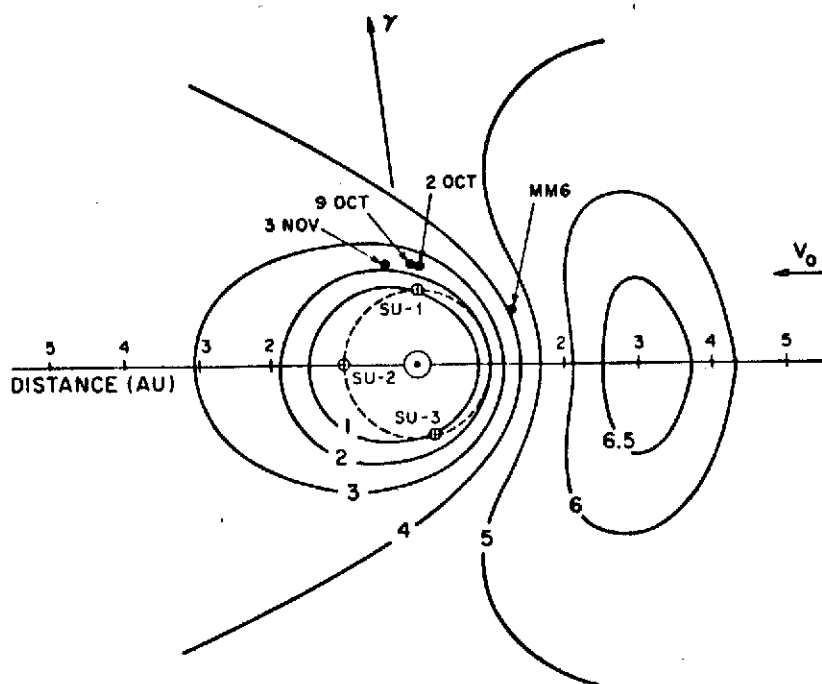


Fig. 12 Volume emission rate contours ($\text{ph cm}^{-3} \text{sec}^{-1}$) in the ecliptic plane, calculated from the model of Bertaux *et al.*¹⁶. The model is for $T = 6000^\circ\text{K}$, $v_0 = 3 \text{ km sec}^{-1}$, and $\mu = 1$. The direction of the vernal equinox is labelled γ ⁴⁷.

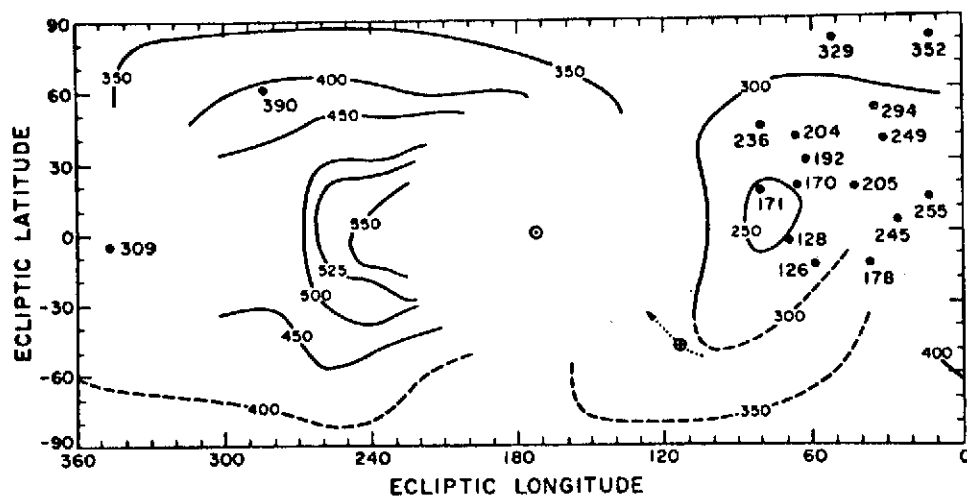


Fig. 13 OGO-5 isophotal contour map (SU-1). The Mariner 9 observations are located at the points labelled with the intensity in Rayleighs. This figure is taken from Bohlin⁴⁷.

Bohlin⁴⁷ and by Thomas and Krassa⁹, this effect is particularly important when the photometer pointed closer than 90° to earth. When the two sets of data are normalized to one another at the maximum, the contribution to the minimum region from the sky background would be only 120 Rayleighs in the OGO-5 maps. This implies a max/min ratio of 4.5 ± 0.5 , which should be considered more accurate than the previously reported ratios of 2.38⁸ and 2.45¹⁶.

More recently, additional deep-space Ly- α data has become available from the Ultraviolet Spectrometer Experiment on the Apollo 17 Command Module²⁵. Over a period of three days during the trans-earth coast of the mission, the Command Module was placed in various spinning modes. Data from the large number of scans of the sky should yield the most accurate and detailed deep-space map yet available. Preliminary indications bear out the results from the Mariner 9 experiment of a low-intensity minimum region.

New evidence concerning the absolute value of the solar Ly- α flux has also been recently reported. From an analysis of the measured curvature of the atomic hydrogen tail of Comet Bennett from the same OGO-5 photometer, Keller and Thomas⁴⁸ derive a new value for the line-center solar Ly- α flux. Their results, based upon purely dynamical considerations of radiation pressure and hence independent of instrumental calibration, show that the effective flux near the line center on March 20, 23, and 25, 1970 was 9.8×10^{11} , 10.5×10^{11} , and 9.2×10^{11} photons $\text{cm}^{-2} \text{sec}^{-1} \text{\AA}^{-1}$. Correcting for the Doppler shifts of the rapidly moving hydrogen atoms using the Bruner and Rense⁴⁹ solar line profile gives an average of 7.6×10^{11} photons $\text{cm}^{-2} \text{sec}^{-1} \text{\AA}^{-1}$. The importance of this result is the fact that at these values, the radiation pressure force is 2.27 times the solar gravitational force!

As will be seen shortly there is a considerable uncertainty in the value of μ and its solar variability. In most papers^{7,50,1,2,24}, the value of μ over the solar cycle has been assumed to be less than unity. Tinsley⁵, Thomas⁸, and Bertaux *et al.*¹⁶ used $\mu = 1$ (corresponding to a line-center flux F_0 of $3.32 \times 10^{11} \text{ ph cm}^{-2} \text{sec}^{-1} \text{\AA}^{-1}$). A few models were considered by Bertaux *et al.*¹⁶ for which $\mu = 1.26$. The Bruner and Rense⁴⁹ profile is shown in Fig. 14 along with representative Doppler absorption widths and line shifts.

To further examine this question we consider the work of Meier and Mange⁵¹ who recently compiled a list of Ly- α airglow measurements from various spacecraft. An effort was made to

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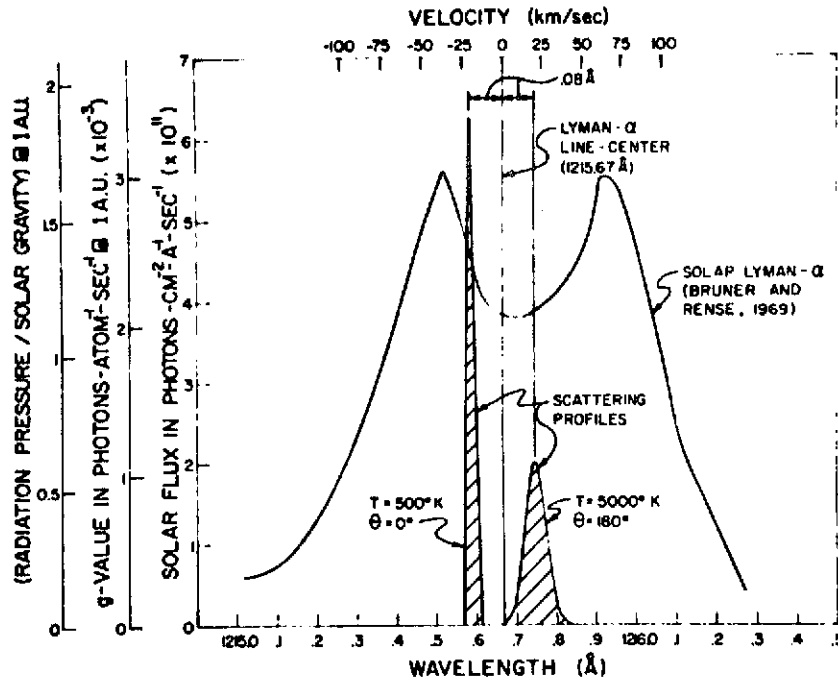


Fig. 14 Solar Ly- α high-resolution line profile measured by Bruner and Rense⁴⁹, normalized to a total flux F of 3.24×10^{11} ph cm⁻² sec⁻¹. Three ordinate scales shown on the left are: μ = radiation pressure/solar gravity, g -value = number of photons scattered per second, and F_λ = solar flux per unit wavelength interval. The upper abscissa is the velocity that corresponds to the Doppler shift indicated on the lower scale. The two scattering profiles apply to two different temperatures, and for two different velocities (+20 km sec⁻¹ and -20 km sec⁻¹).

compare them at nearly the same altitude, look direction, and solar zenith angle. Any differences in the results are due to solar activity (which affects both the Ly- α solar flux and the exospheric temperature) and discrepancies in absolute calibration of the various experiments. Meier and Mange⁵¹ used a geocoronal model and corrected for the atmospheric temperature according to the Jacchia method for the particular times of each measurement. A further correction, using an empirical correlation between F_0 and Zurich sunspot number, placed all measurements on essentially the same observing

basis. The remaining discrepancies are due largely to calibration differences. The results for F_O fall within the large range of 2.4×10^{11} to 8.0×10^{11} ph cm⁻² sec⁻¹ A⁻¹.

Direct measurements of F_O were made by a resonance scattering cell on OSO-5⁵². During 1969 and 1970, F_O varied between 3 and 5×10^{11} ph cm⁻² sec⁻¹ A⁻¹ and was well correlated with the total Ly- α flux F . The average of all the moderate-to-high solar activity airglow measurements, including the determination of Keller and Thomas⁴⁸, is in good agreement with the OSO-4 airglow results of Meier and Mange⁵¹. These are in excellent agreement with the measurements of Vidal-Madjar *et al.*⁵², in both magnitude and in their dependence on sunspot number. The best-fit linear correlations are given by:

$$F_O = 3.65 + .01104 R_Z \quad (\times 10^{11} \text{ ph cm}^{-2} \text{ sec}^{-1} \text{ A}^{-1}) \quad (6a)$$

$$\mu = 1.10 + 3.325 \times 10^{-3} R_Z \quad (6b)$$

where R_Z is the Zurich sunspot number.

We may compare the above variation with that of the total flux, F . Weeks⁵³ compiled the results for 23 rocket experiments and showed that this quantity also underwent a solar cycle variation, from $2.63 \pm 0.21 \times 10^{11}$ ($R_Z < 40$) to $3.73 \pm 0.28 \times 10^{11}$ ph cm⁻² sec⁻¹ ($R_Z > 40$). This suggests that the solar cycle variation is similar but of smaller magnitude than that of F_O . Within the uncertainties, the data compiled by Weeks do not contradict the findings of Vidal-Madjar *et al.*⁵², namely that F_O increases 60% faster than F with solar activity.

Most of the evidence appears to support a net repulsive force on hydrogen atoms, from perhaps 10% greater than solar gravity at solar minimum ($\mu = 1.10$) to 76% greater ($\mu = 1.76$) at solar maximum. This contradicts the conclusions of Fahr⁵⁰ who adopted a 30% variation over the 11-year solar cycle, ranging from $\mu = 0.40$ at solar minimum to $\mu = 0.70$ at solar maximum. Fahr⁵⁰ assumed that the value of F at solar minimum is 2.69×10^{11} ph cm⁻² sec⁻¹ and at solar maximum is 4.65×10^{11} ph cm⁻² sec⁻¹. These values are not inconsistent with the results reported by Weeks⁵³. He used a conversion factor F/F_O of only 0.5A on the basis of the high-resolution profile of Tousey⁵⁴. However, this is too small a value since, even for the quiet solar regions (where the chromospheric absorption produces a more self-reversed line), I find that from

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the Tousey⁵⁴ profile in the paper by Meier and Prinz⁵⁵ the conversion factor is 0.66A. This underestimate of F/F_0 , combined with the larger fluxes from airglow results provides the explanation for Fahr's⁵⁰ values lying a factor of 2.5 - 2.75 below those predicted by Eq. (6).

What consequence does a net repulsion have on models of interplanetary hydrogen? First, it means that no enhancement of hydrogen density on the downwind axis is expected. The absence of an intensity peak in the vicinity of the Ly- α minimum is thus naturally explained (although as pointed out by Johnson³⁰ such a feature might be difficult to observe unless the geometry is particularly favorable). Second, it means that gravitational focussing plays no role in determining the density in the downwind direction - the density in this direction must be attributed to velocity dispersion in the interstellar gas or possibly to scattering of the incoming atoms by solar wind electrons³⁶. Third, it implies the existence of an interesting region in the outer solar system, an "atomic hydrogen sheath."

VII. The Atomic Hydrogen Sheath

When $\mu > 1$, atoms of velocity v_0 are prevented from entering a paraboloidal region $r_p(\theta)$, given by

$$r_p(\theta) = 2r_p(0)/(1 + \cos\theta) \quad (7)$$

where θ is the angle between \vec{r} and $-\vec{v}_0$. If \vec{v}_0 is the only component present in the gas (i.e., a cold model), then a density singularity will exist on the surface defined by $r_p(\theta)$. This is easily seen if the equations of Blum and Fahr¹² and Holzer¹⁵ (see Johnson³⁰ for a summary of Holzer's work) are written in terms of the variable x where

$$x = (1 - r_p(\theta)/r)^{1/2}$$

$$n(x) = (n_\infty/4x) \sum_{j=1}^2 (1 + p_j x)^2 \exp\left\{-(2r_i(\theta)/r_p(\theta))(1 - p_j x)\right\} \quad (8)$$

where $r_i(\theta) = r_i(0) \sin\theta/\theta$ and where $p_1 = 1$, $p_2 = -1$. Note that as $r \rightarrow r_p(\theta)$, $x \rightarrow 0$, and $n \rightarrow \infty$. Note also that as $r \rightarrow \infty$, $x \rightarrow 1$, and $n \rightarrow n_\infty$.

Even though temperature effects are dominant in determining the distribution for $\theta > 90^\circ$, they are not very important in the forward hemisphere⁵⁰. Thus we expect the

intensity calculated on the basis of a 'cold' model to be approximately correct for $0^\circ \leq \theta \leq 90^\circ$. We can calculate the first-order scattering intensity by integrating the quantity $g_e n(r, \theta) r_e^2 / r^2$ from the radial distance of observation, r_0 over the line of sight. g_e is the resonance g-factor at $r = r_e$. For $r_e = 1$ A.U. and for a sunspot number of 100 (appropriate to the spin-up periods in 1969 and 1970) $g_e = 2.56 \times 10^{-3} \text{ sec}^{-1}$ ($\mu = 1.43$).

The single-scattering intensity for observation in the radially-outward direction is given by

$$4\pi I = g_e r_e^2 \int_{r_0}^{\infty} n(r) \bar{r}^{-2} dr \quad (9)$$

In terms of the variable x , Eq. (9) can be integrated analytically for the radially-outlooking case. For $r_0 = 0$, the result is

$$4\pi I = g_e n_{\infty} (r_e^2 / r_p(0)) (1 + \cos \theta) \zeta(y) \quad (10)$$

where
$$\zeta(y) = (2y^2 - 2y + 1 - e^{-2y}) / 2y^3 \quad (11)$$

and
$$y = 2 r_i(\theta) / r_p(\theta) \quad (12)$$

Note that the integration over the density singularity has been achieved analytically. This is not possible for look directions other than along \hat{r} . For the limit $y \rightarrow 0$, $\zeta(y) \rightarrow 2/3$; for $y \rightarrow \infty$, $\zeta(y) \rightarrow (1/y)$. $y \approx 0$ occurs when $r_i(\theta) \ll r_p(\theta)$, i.e., when ionization of the incoming atoms is negligible in determining the intensity. The opposite limit ($y \rightarrow \infty$) occurs if ionization is dominant and dictates the shape of the cavity. The latter case is more appropriate for the hydrogen problem, where $4.85 < y < 15.2$ for the parameters assumed in Section 3. Thus

$$4\pi I \approx g_e n_{\infty} (r_e^2 / r_i(0)) (\sin \theta / \theta) \quad (13)$$

Equation (13) is the same as the prediction for the perfect balancing case ($\mu = 1$). It implies that ionization occurs at sufficiently great distances where dynamical acceleration of the incoming atoms can be ignored. Thomas⁸ has shown that for $\theta < 90^\circ$, Eq. (13) provides an adequate fit to the shape of the OGO-5 data in the ecliptic plane. Figure 15 shows model density contours for $T = 0^\circ\text{K}$ when $r_i(0) = 3.2$ A.U. The



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latter value is consistent with the OGO-5 seasonal parallactic displacement of the sky maximum of 38° . For $\theta > 90^\circ$, the hot model must be used to explain the observations if we ignore the possibilities of a galactic background and a diffuse multiple-scattering component.

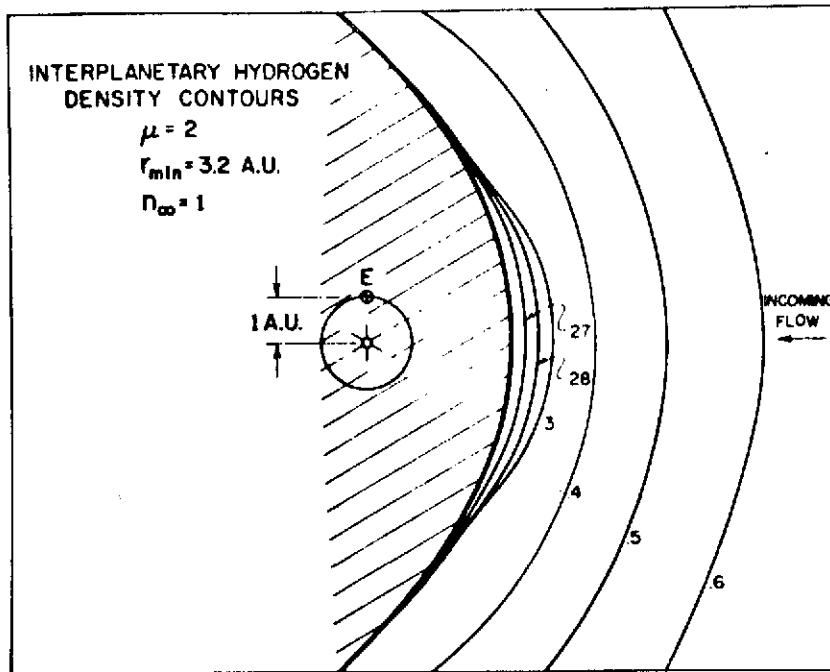


Fig. 15 Contours of equal density for a large radiation pressure/solar gravity ratio. The velocity has been adjusted to $v_0 = 32.5 \text{ km sec}^{-1}$ so that the hydrogen sheath (solid line) is located at the position indicated by the OGO-5 parallax of 38° .

All the OGO-5 maps have been corrected for geocoronal contamination in the maximum and minimum regions (see Table 1, Thomas and Krassa⁹). As discussed previously the new results indicate a larger (maximum/minimum) ratio (~ 4) than that deduced from the earlier uncorrected maps (~ 2.4). Taken alone, this would imply a lower temperature for the nearby interstellar medium. However if the Lyman alpha airglow measurements of Meier and Mange⁵¹ and Vidal-Madjar *et al.*⁵² are accepted, we must consider the possibility of a significantly-larger radiation pressure force than heretofore recognized. If this new interpretation is also taken alone it would imply a larger interstellar temperature than earlier estimates. These two influences operating together tend to cancel one another. Work on a detailed model is in progress⁵⁶.

Returning to a description of the hydrogen sheath, we would expect that the effects of temperature will be to smear out the density enhancement, in much the same way that they operate on the helium density enhancement at $\theta = 180^\circ$. Short-term variations in the solar-wind flux and in the Lyman alpha photon flux would also produce a similar effect. However, it may be possible to determine the extent of the smearing (and hence the temperature) by a careful analysis of Ly- α data measured from an outer-planet spacecraft. The Pioneer 10 and 11 will make such measurements. The predicted positions of the sheath for a number of values of Lyman alpha radiation pressure are shown in Fig. 16. The viewing geometry of the UV experiment is shown in Fig. 17. The photometer will record an almost constant signal until the hydrogen sheath region is penetrated. For a fixed viewing direction the signal would decrease to an extent depending upon the spatial smearing and the viewing direction. The effect would probably be too gradual to observe unless the line-of-sight were closely tangential to the sheath region. If the interplanetary gas were sufficiently cold, an observer located at $r > r_p(\theta)$,

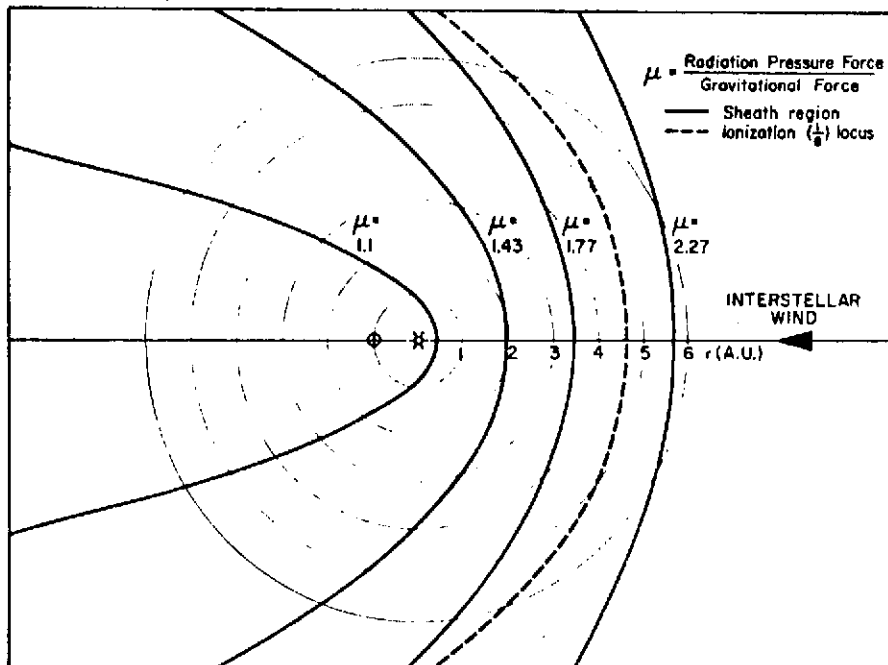


Fig. 16 Boundaries of the forbidden regions due to radiation pressure deflection of the interstellar hydrogen atom trajectories. The dashed curve marks the position of the probability of $(1/e)$ of solar wind charge-exchange, which is probably independent of the solar cycle.

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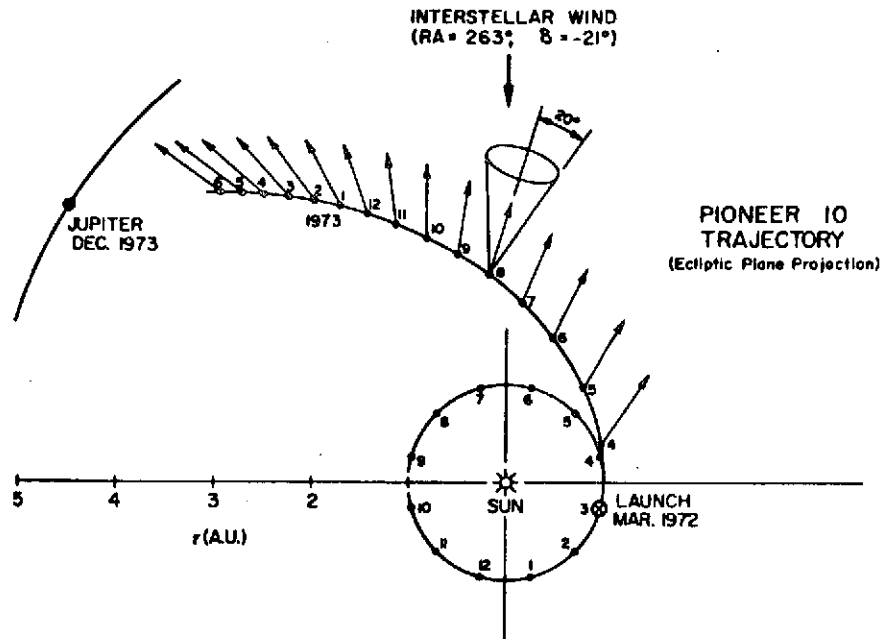


Fig. 17 Trajectory of Pioneer 10 projected on the ecliptic plane. For each month in the year, beginning at launch, the spacecraft spin-axis (arrows) always points to the earth. The center of the field of view of the extreme ultraviolet photometer is shown, which is offset from the spin-axis by 20° . The field of view of the instrument is $1.15^\circ \times 9.3^\circ$, which has a sensitivity of $10 \text{ counts sec}^{-1} \text{ Rayleigh}^{-1}$ at both $\text{Ly-}\alpha$ and at 584\AA .

would see in the light of $\text{Ly-}\alpha$, a "halo" of emission located at an angle α from the antisolar position, given by $\tan \alpha = (1 + \cos \theta) / \sin \theta$, where θ is the angular position of the observer with respect to the wind vector. The combined effects of temperature, solar variability, and ionization of atoms in the sheath region work to reduce the visibility of the region. However, it would be worthwhile to search for this enhancement for observations made beyond $r > r_p(\theta) \approx 2 \text{ A.U.}$ As mentioned previously the above value of $r_p(\theta)$ is highly uncertain because of the uncertainty in v_0 . For the extreme case of $v_0 = 27.6 \text{ km sec}^{-1}$ and $\mu = 1.43$, the earth's orbit would lie outside the hydrogen sheath. Clearly this situation would also occur near solar minimum when μ is smaller, if v_0 were smaller than 27.6 km sec^{-1} .

The $\text{Ly-}\alpha$ data from the two Pioneer missions can add much to our understanding of this problem, particularly if the

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spacecraft could be released temporarily from their present earth-pointing geometry (Fig. 17). This might provide sufficiently good sky coverage to allow for a search for the hydrogen sheath enhancement. Our next chance for this type of measurement will not occur until late in this decade after the launch of the Mariner Jupiter-Saturn experiment payload.

VIII. Conclusions and Prospects

In summary, recent measurements of the Ly- α HI 1216A and He I 584A extraterrestrial emission lines have provided new information on the interplanetary distributions of H and He. Unfortunately, the fact that there are three parameters of the interstellar gas (flow velocity, density, and temperature) prevents us from determining all of them independently. In addition, uncertainties in the ionization rates and (particularly) in the solar Ly- α flux produce additional uncertainties into the models. I would attach the following range of values to these quantities: $n_{\infty}(\text{H})$ ($0.05 - 0.2 \text{ cm}^{-3}$), T ($1000^{\circ}\text{K} - 12,000^{\circ}\text{K}$), v_0 ($3 - 30 \text{ km sec}^{-1}$) and $n_{\infty}(\text{He})$ ($1 \times 10^{-3} - 2 \times 10^{-2} \text{ cm}^{-3}$); for the solar parameters, $J_e(\text{He})$ ($0.5 - 0.8 \times 10^{-7} \text{ sec}^{-1}$), $J_e(\text{H})$ ($4 - 8 \times 10^{-7} \text{ sec}^{-1}$), $F_0(1216\text{A})$ ($3 - 8 \times 10^{11} \text{ ph cm}^{-2} \text{ sec}^{-1} \text{ A}^{-1}$), and $F_0(584\text{A})$ ($10^{10} - 10^{12} \text{ ph cm}^{-2} \text{ sec}^{-1} \text{ A}^{-1}$).

It is obvious that there exists a great deal of room for improvement. Aside from the outer-planet missions, perhaps the most promising experiment would be one which measures the line profile of the emission lines. This would yield direct information on both temperature and flow velocity even though complications of Doppler shifts would be difficult to interpret. Unless such an experiment could be placed on a deep-space mission, the most suitable line profile to measure would be that of the 584A line. This could be accomplished with a conventional photometer with a helium absorption cell in the optical path. A programmed variation of the helium pressure could produce a large range of absorption optical depths. The line profile could be retrieved by a process of unfolding the helium cell absorption profile from an assumed incoming line profile. Such an experiment is planned for the 1975 Apollo-Soyuz orbital mission by the Berkeley group. A map of the sky at effectively very high spectral resolution can provide an unambiguous determination of nearly all the physical properties of the nearby interstellar gas.

Postscript

Since the above was written a number of new developments have occurred. The following is a brief summary of work that



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bears directly on the content of this review. It describes recent measurements which were reported after August 1973.

There are now available two high-resolution measurements of the solar He I 584A line profile, one by Doschek *et al.*⁵⁸ and another by Cushman *et al.*⁵⁹. As reported by Weller and Meier⁶⁰, the former group found a full width at half maximum of 0.15A. This is in reasonable agreement with the preliminary results of Cushman *et al.*⁵⁹ of 0.11A. However corrections had to be applied to the observed line profile to take into account the presence of a solar line from an overlapping spectral order, and more importantly the effect of geocoronal absorption at rocket altitudes. The improved values of Cushman *et al.*⁵⁹ indicate a smaller line width for quiet regions (which are appropriate to the integrated solar disc emission) of 0.08A. The values of the total flux and the solar flux at line center were 1.3×10^9 ph cm⁻² sec⁻¹ and 1.7×10^{10} ph cm⁻² sec⁻¹ respectively. The former is in agreement with previous measurements by Tousey *et al.*⁶¹. The latter is five times smaller than that deduced indirectly from airglow measurements by Donahue and Kumer³³ and Paresce *et al.*⁶⁴. The line-center flux is only a factor of about two smaller than the rocket airglow values of Weller and Meier⁶⁰ of 3.7×10^{10} ph cm⁻² sec⁻¹ A⁻¹. They are in excellent agreement with the recent analysis by Meier and Weller⁶¹ of satellite airglow measurements who obtained a line center flux of 2×10^{10} ph cm⁻² sec⁻¹ A⁻¹. It also appears to be consistent with a recent lower limit of 0.15A for the line width determined from OSO-6 measurements of the absence of geocoronal attenuation of the integrated line⁶². Unfortunately in their analysis of the 584A extraterrestrial component, Weller and Meier⁶⁰ used the uncorrected line width of Doschek *et al.*⁵⁸ which resulted in a value of the line-center flux (6.6×10^9 ph cm⁻² sec⁻¹ A⁻¹) which is probably too small. A more serious problem in their analysis could be the failure to take into account Doppler shifts between the wind and the sun. These would be unimportant for a line width of 0.15A. However according to Weller and Meier⁶⁰ a line width less than 0.10A might significantly alter their conclusions in their analysis of the extraterrestrial 584A data.

The above remarks do not apply to the analysis of recent rocket measurements of extraterrestrial 584A by Paresce *et al.*⁴¹ who included a correction for geocoronal absorption of the measurements of Cushman *et al.*⁵⁹. They found a best-fit model which implied a solar line width of 0.15A. In addition their model had a temperature of 10^4 °K and a helium density, n_{He} , of 0.032 cm⁻³. The rocket measurement of Paresce *et*

al.^{63,41} have provided the first positive evidence of extra-terrestrial helium emission. The much more extensive results from the STP-72-1 satellite 584A airglow measurements now provide conclusive proof⁶⁰. When the nighttime data for an entire year were analyzed, a full sky map could be created. This revealed a down-wind focussing peak with a maximum intensity of 9 Rayleighs and a full width at half-maximum of 50° . This result provides a dramatic confirmation of the interstellar wind theory deduced from the Lyman alpha sky maps. Using a theoretical model of Feldman et al.²³ for the downwind density distribution, Weller and Meier⁶⁰ found best-fit models of the interplanetary distribution. As in the earlier Lyman alpha models it was not possible to determine a unique model since several parameters are involved. The range of values of the interstellar parameters allowed by the STP-72-1 results are: $V_0 = 5-20 \text{ km sec}^{-1}$, $T = 2,500 - 10,000^\circ\text{K}$, and $n_{\text{He}} = 0.009 - 0.024 \text{ cm}^{-3}$. On comparing the possible ranges of these parameters in the suggested Conclusions section of this paper, this represents a considerable improvement in our knowledge of the flow speed and interstellar gas temperature. In addition, because of the sharpness of the downwind focussing maximum, we now have an accurate determination of the direction of the wind. Correcting for parallax, Weller and Meier⁶⁰ found that the downwind vector is at $\text{RA} = 72^\circ$, $\delta = +15^\circ$. This represents a wind vector emerging from the direction $\text{RA} = 252^\circ$, $\delta = -15^\circ$ with an uncertainty of $\pm 3^\circ$. This is some 12° away from the average value for the OGO-5 Lyman alpha maps of Bertaux and Blamont⁶ and Thomas and Krassa⁹. The discrepancy can be attributed in part to an inherently smaller accuracy in defining the broad Lyman alpha upstream peak, and to errors introduced by Lyman alpha geocoronal contamination of the sky maps. As mentioned previously, Judge and Carlson's⁴⁴ preliminary model which best fit their Pioneer 10 Lyman alpha data gave a wind direction in the ecliptic at $\text{RA} = 240^\circ$. Full-sky 584A maps (as well as 1216A maps) can be expected to appear soon as a result of interplanetary measurements made by the Mariner 10 UV spectrometer in early 1974.

Additional unpublished information from an analysis of Apollo 17 Lyman alpha sky background data is now available. The position of the minimum feature in December 1972 was $\text{RA} = 65^\circ$, $\delta = +5^\circ$ with an error of $\pm 10^\circ$ on each value. Since a negligible parallax correction is involved, this implies a wind vector position of 245° , $\delta = -5^\circ$, in essential agreement with the STP-72-1 results. Taken together with the Pioneer 10 results discussed in the text, it seems virtually certain that in the time period 1972-1973, the interstellar wind direction was appreciably different from that deduced



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from OGO-5 results in 1969-1970. This could be caused by: (1) an unexplained time-dependent motion of the apparent wind vector, (2) the OGO-5 maps contain an unknown systematic error, or (3) the effects of solar Lyman alpha anisotropies are sufficiently strong to produce shifts in the position of the maximum, as first advocated by Fahr and Lay¹⁷.

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